Displacement Current and Surface Flashover

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Abstract

High-voltage vacuum insulator failure is generally due to surface flashover rather than insulator bulk breakdown. Vacuum surface flashover is widely believed to be initiated by a secondary electron emission avalanche along the vacuum-insulator interface. This process requires a physical mechanism to cause secondary electrons emitted from the insulator surface to return to that surface. Here, we show that when an insulator is subjected to a fast high-voltage pulse, the magnetic field due to displacement current through the insulator can provide this mechanism. This indicates the importance of the voltage pulse shape, especially the rise time, in the flashover initiation process.

Insulators subjected to high voltage in vacuum tend to fail through the process of surface flashover. While there remains debate regarding the mechanism for surface flashover,[1] secondary electron emission avalanche (SEEA) has emerged as the dominant theory. In this model,[2,3] electrons are field-emitted from the cathode triple junction formed by the intersection of the vacuum, the electrode, and the insulator, where field enhancement may occur[4]. These electrons strike the insulator surface and produce secondary electrons, which also strike the surface to produce additional secondaries and form the avalanche. The secondary yield depends in part on the energy of the incident electrons; if this yield is not equal to one, surface charging occurs which alters electron trajectories. This serves as a feedback mechanism to keep the yield in a saturated avalanche equal to one. Electron bombardment of the insulator surface causes adsorbed gas to be released into the vacuum, and it is through this gas that the flashover occurs.

Although the establishment of a saturated SEEA is usually assumed to precede surface flashover, certain aspects of the avalanche initiation process remain unclear. Primary electrons emerging from the triple junction and secondary electrons emerging from the insulator have an initial velocity directed away from the insulator. A physical mechanism is required to deflect these electrons towards the insulator. This deflection is usually assumed to be a result of positive charging of the insulator surface.[2,5]

Displacement current may play a similar role in altering the electron trajectories when the rate of change of voltage is sufficiently high, allowing flashover initiation in the absence of a pre-existing surface charge. For a solid cylindrical insulator between parallel plate electrodes, the displacement current during the leading edge of an applied voltage pulse will generate a magnetic field parallel to the insulator surface, which will

cause electrons emitted from the surface or the triple junction to be deflected towards the surface (Fig. 1). Whether a given electron will strike the surface depends on its emission angle and energy, as well as dV/dt and the geometry and material properties of the insulator. During the trailing edge of the pulse, electrons will be deflected away from the surface. The same effect will cause electrons to be deflected away from the interior surface of a hollow, cylindrical insulator during the leading edge, and deflected towards the interior surface during the trailing edge.

The influence of magnetic fields on surface flashover is well known,[6-8] and is one of the arguments in support of the SEEA theory. However, these effects generally rely on externally-generated magnetic fields[9], or self-fields due to conduction currents in transmission lines[6,8,10] or high-current electron beams in diodes[6], rather than the result of magnetic fields generated by displacement current.

To address this problem mathematically, we assume that electrons are produced from the surface of a cylindrical insulator placed in a uniform, coaxial electric field. Electrons are released with a small initial velocity perpendicular to the surface, which is the most likely direction for electrons produced by secondary emission.[11] Nonrelativistic electron motion is assumed and space charge is neglected.

The applied electric field is assumed to have the form

$$E(t) = \frac{E_0}{\tau} t, \tag{1}$$

where E_0 is the peak applied electric field and τ is the rise time (only the period $0 \leq t \leq \tau$ is considered). The magnetic field at the insulator surface is calculated from Ampere's law, using the displacement current $C\dfrac{dV}{dt}$:

$$B = \frac{\mu_0 C}{2\pi a} \frac{dV}{dt} = \frac{\mu_0 C E_0 d}{2\pi a \tau} \ . \tag{2}$$

The capacitance C is due to the presence of the insulator between the parallel plate electrodes, and d is the insulator length. As long as electrons remain sufficiently close to the surface, we can neglect the insulator curvature and proceed with rectangular coordinates. The magnetic field is along the $\hat{x}$-direction, the electric field is along the $\hat{y}$-direction, and the initial velocity is along the $\hat{z}$-direction. The equations of motion are:

$$\frac{dv_y}{dt} = \frac{-e}{m}\left[E_y + v_z B_x\right] \tag{3}$$

and

$$\frac{dv_z}{dt} = \frac{e}{m} v_y B_x , \tag{4}$$

where $e = -1.6 \times 10^{-19} C$. Electrons are released from the surface at time t_0 ($0 \le t_0 < \tau$). Solving these equations for the initial conditions $v_z(t_0) = v_0$, $v_y(t_0) = 0$ gives the z and y velocities

$$v_z(t) = \frac{-E_0 t}{B\tau} + \alpha \sin(kt) + \beta \cos(kt) \tag{5}$$

$$v_y(t) = \frac{-E_0}{B\tau} + \alpha \cos(kt) - \beta \sin(kt) \tag{6}$$

and positions

$$z(t) = -\frac{E_0}{B}\frac{t^2}{2\tau} - \frac{\alpha}{k}\cos(kt) + \frac{\beta}{k}\sin(kt) + \Gamma \tag{7}$$

$$y(t) = -\frac{E_0}{k\tau B}t + \frac{\alpha}{k}\sin(kt) + \frac{\beta}{k}\cos(kt) + \Lambda \ . \tag{8}$$

The constants in eqs. (5-8) are given by

$$\alpha = \frac{E_0}{k\tau B}\left[\cos(kt_0)\right]^{-1} + \left[v_0 + \frac{E_0 t_0}{B\tau}\right]\sin(kt_0) - \frac{E_0}{k\tau B}\sin(kt_0)\tan(kt_0), \quad (9)$$

$$\beta = \left[v_0 + \frac{E_0 t_0}{B\tau}\right]\cos(kt_0) - \frac{E_0}{k\tau B}\sin(kt_0), \quad (10)$$

$$\Gamma = \frac{E_0}{B}\frac{t_0^2}{2\tau} + \frac{\alpha}{k}\cos(kt_0) - \frac{\beta}{k}\sin(kt_0), \quad (11)$$

$$\Lambda = \frac{E_0}{k\tau B}t_0 - \frac{\alpha}{k}\sin(kt_0) - \frac{\beta}{k}\cos(kt_0), \quad (12)$$

and

$$k = \frac{Be}{m}. \quad (13)$$

These equations were used to calculate the trajectories of electrons emitted at $t_0 = 0$ from an insulator with a radius of 1 cm, height of 1 cm, and capacitance of 1.5 pF ($\varepsilon_r \approx 5.4$). Initial electron energy was 2 eV. Fig. 2 shows these electron trajectories for an applied electric field rising to 100 MV/m in 10 ns, corresponding to a magnetic field of 3 mT (solid lines), compared with trajectories calculated assuming a negligible magnetic field (dotted lines). Note that this field is much weaker than the 0.1-1 T required for magnetic insulation by $\bar{E} \times \bar{B}$ drift [9]. Some electrons are able to strike the surface; their time of flight is 0.28 ns, and they strike with a kinetic energy of 13.3 keV. Fig. 3 shows the same case, except that electrons are released at $t_0 = 5$ns; electron time of flight with the 3 mT magnetic field is 33 ps and their kinetic energy at impact is 240 keV. The inset to Fig. 3 shows good agreement between the analytic calculation and simulations performed using the particle-in-cell code LSP[12].

Fig. 4 shows the kinetic energy at impact as a function of voltage slew rate for electrons emitted at $t_0 = 0$. Curves are shown for several values of electron emission energy. Larger initial energies and smaller voltage slew rates enable electrons to travel longer distances and gain more energy before striking the insulator surface. If the electron range is large enough, it will strike the anode instead of the insulator surface; the combined action of the electric and magnetic fields can focus the electron trajectories on a small region of the electrode, which in principle could trigger a vacuum arc. Of critical importance is the electron impact energy compared to the first and second crossover energies of the insulator, the values of primary electron energy at which the secondary yield is one[11]. Fig. 4 shows that most electrons will strike with an impact energy greater than the typical second crossover energy of 1 keV, and therefore will charge the surface negatively. The stable operating point of a resulting saturated SEEA would therefore occur at the second crossover energy.[2] However, positive charging may also be possible, as the secondary yield is expected to increase dramatically for grazing-incidence impacts, as would be the case here [13].

These calculations show that for sufficiently large dV/dt, the displacement current through an insulator can generate a magnetic field causing electrons produced at the insulator surface to return to the surface. This mechanism applies equally to electrons produced by field emission from the cathode triple junction and secondary emission on the insulator surface. This magnetic field therefore allows an initial electron bombardment of the surface, and initiation of SEEA, without requiring a pre-existing surface charge. It also illustrates the important role played by the amplitude, rise time, and shape of the applied pulse in the vacuum surface flashover process.

ACKNOWLEDGMENT

REFERENCES

[1]H.C. Miller, IEEE Trans. Elect. Insul. **24** 765 (1989).

[2]H. Boersch, H. Hamisch, and W. Ehrlich, Z. Angew. Physik **15** 518 (1963).

[3]R. A. Anderson and J. P. Brainard, J. Appl. Phys. **51** 1414 (1980).

[4]M.S. Chung, B.-G. Yoon, P.H. Cutler, and N.M. Miskovsky, J. Vac. Sci. Technol. B **22** 1240 (2004).

[5]K.D. Bergeron, J. Appl. Phys **48** 3073 (1977).

[6]J.P. VanDevender, D.H. McDaniel, E.L. Neau, R.E. Mattis, and K.D. Bergeron, J. Appl. Phys. **53** 4441 (1982).

[7] R.A. Anderson, Appl. Phys. Lett **24** 54 (1974).

[8] K.D. Bergeron and D.H. McDaniel, Appl. Phys. Lett **29** 534 (1976).

[9] R. Korzekwa, F.M. Lehr, H.G. Krompholz, and M. Kristiansen, IEEE Transactions on Plasma Sci. **17** 612 (1989).

[10] M.E. Savage, W.A. Stygar, J.M. Elizondo, H.C. Ives, W. Shoup, K.W. Struve, and D.H. McDaniel, Proc. 2004 Power Modulatior Conference, San Francisco, CA, 23-26 May 2004.

[11]K.R. Spangenberg, *Vacuum Tubes*, Ch. 4, McGraw-Hill: New York (1948).

[12] R.E. Clark and T.P. Hughes, LSP User's Manual and Reference, Version 8.8, 3 Oct. 2005.

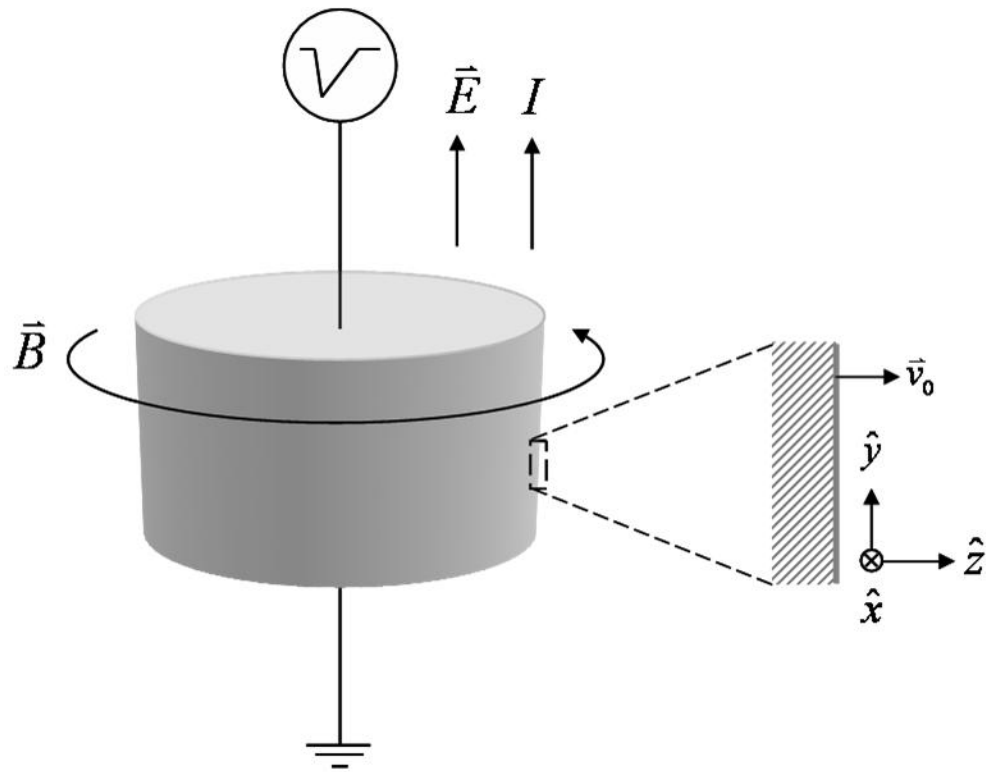[13] RA Anderson J. Appl Phys **48** 4210 (1977).

Fig. 1. Calculation geometry. Parallel plate electrodes are assumed, but not shown in this figure. For Figs. 2-4, an insulator radius of 1 cm, height of 1 cm, and capacitance of 1.5 pF were used.
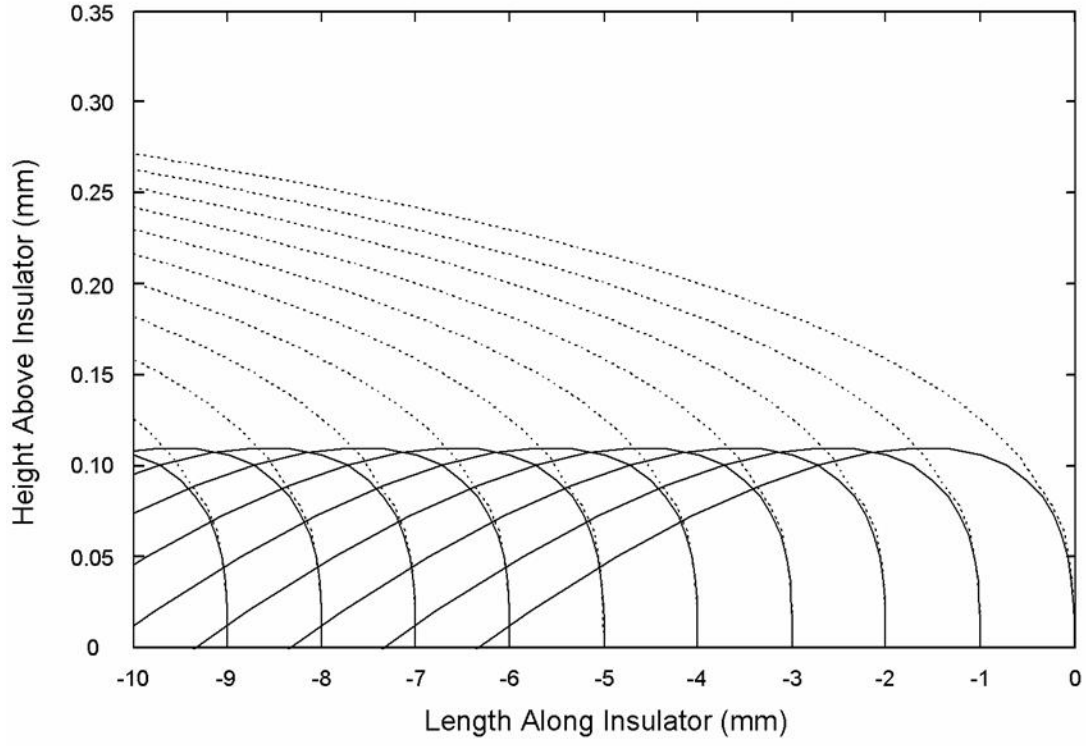
Fig 2. Electron trajectories with (solid) and without (dot) magnetic field due to displacement current, for electrons emitted at $t_0 = 0$.
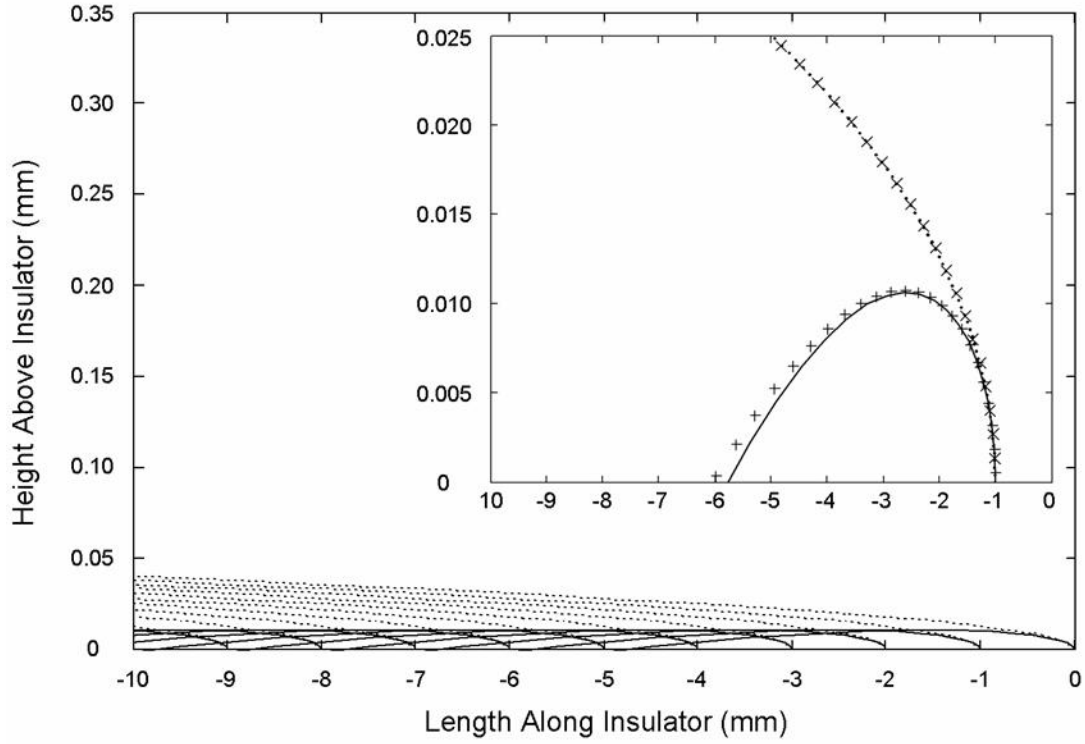
Fig 3. Electron trajectories with (solid) and without (dot) magnetic field due to displacement current, for electrons emitted at $t_0 = 5ns$. Inset shows comparison between theory with (solid) and without (dot) magnetic field and simulation results from LSP with (+) and without (x) magnetic field.
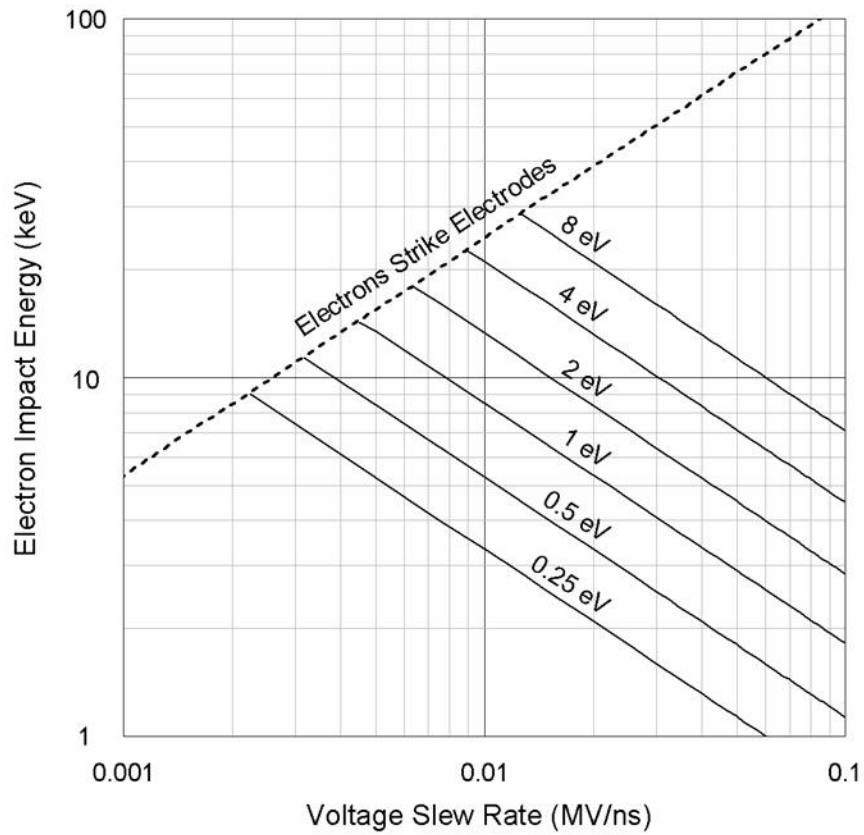
Fig. 4. Electron kinetic energy on impact, as a function of voltage slew rate. Curves for several electron initial energies are shown.